10/518597
DT12 Rec'd PCT/PTO 21 DEC 2004

PART CAST FROM ALUMINIUM ALLOY WITH HIGH HOT STRENGTH

Domain of the invention

The invention relates to cast parts made of aluminium alloy subjected to high thermal and mechanical stresses, particularly cylinder heads and crankcases of internal combustion engines, and more particularly turbocharged diesel or gasoline engines. It also relates to parts other than automobile parts subjected to the same types of stress, for example in mechanics or in aeronautics.

State of the art

Two families of aluminium alloys are usually used for the manufacture of engine cylinder heads:

1) alloys containing 5 to 9% of silicon, 3 to 4% of copper and magnesium. They are usually secondary alloys, with iron contents of between 0.5 and 1%, and fairly high contents of impurities, particularly manganese, zinc, lead, tin or nickel. These alloys are generally non-heated alloys (temper F) or simply stabilised (temper T5). They are used particularly for manufacturing cylinder heads for gasoline engines with fairly low temperature stresses. For more highly stressed parts intended for diesel or turbo-diesel engines, primary alloys are used with an iron content of less than 0.3%, heat treated to temper T6 (tempered to the peak mechanical strength) or T7 (over-ageing).

2) primary alloys containing 7 to 10% of silicon and magnesium treated to temper T6 or T7, for more highly stressed parts like those intended for use in turbo-diesel engines.

These two large families of alloys require different compromises between various usage properties: mechanical strength, ductility, creep resistance and fatigue resistance. For example, this problem has been described in the article by R. Chuimert and M. Garat: "Choice of aluminium casting alloys for highly stressed diesel cylinder heads", published in the SIA Review, March 1990. This article summarises the properties of 3 alloys studied as follows:

- Al-Si5Cu3MgFe0.15 T7: high strength – good ductility

- Al-Si5Cu3MgFe0.7 F: high strength, low ductility
- Al-Si7Mg0.3Fe0.15 T6: low strength, extreme ductility.

The first and third alloy-temper combinations may be used for highly stressed cylinder heads. However, attempt continued to find an improved compromise between strength and ductility. Patent FR 2690927 issued by the inventors and deposited in 1992 describes aluminium alloys resistant to creep containing 4 to 23% of silicon, at least one element among magnesium (0.1 – 1%), copper (0.3 –4.5%) and nickel (0.2 – 3%), and 0.1 to 0.2% of titanium, 0.1 to 0.2% of zirconium and 0.2 to 0.4% of vanadium. An improved creep resistance is observed at 300°C with no significant loss in the elongation measured at 250°C.

The article by F.J. Feikus "Optimisation of Al-Si cast alloys for cylinder head applications" AFS Transactions 98-61, pp. 225-231, studies the addition of 0.5% and 1% of copper to an AlSiMg0.3 alloy for manufacturing cylinder heads for internal combustion engines. No improvement in the yield stress and no increase in the hardness at ambient temperature was observed after conventional T6 treatment involving 5 h dissolution at 525°C followed by quenching in cold water and annealing for 4 h at 165°C. The added copper only makes a significant improvement to the yield stress and creep resistance at usage temperatures of more than 150°C.

Patent EP 1057900 (VAW Aluminium) deposited in 1999 is a development along the same direction and describes the addition of closely controlled quantities of iron (0.35 – 0.45%), manganese (0.25 – 0.30%), nickel (0.45 – 0.55%), zinc (0.10 – 0.15) and titanium (0.11 – 0.15%) to an Al-Si7Mg0.3Cu3.5 alloy. This alloy has good creep resistance, high thermal conductivity, satisfactorily ductility and good resistance to corrosion, in the T6 and T7 tempers.

The purpose of this invention is to further improve the mechanical strength and creep resistance of cast parts made of AlSiCuMg type alloys within the temperature range 250-300°C, without degrading their ductility, and avoiding the increased use of alloying elements that can cause problems in recycling.

Purpose of the invention

The purpose of the invention is a cast part with high mechanical strength when hot and high creep resistance, made of an alloy with composition (% by weight):

Si: 5 - 11	and preferably 6.5 - 7.5		
Fe < 0.6	and preferably < 0.3		
Mg: 0.15 - 0.6	"	"	0.25 – 0.5
Cu: 0.3 - 1.5	"	"	0.4 - 0.7
Ti: 0.05 - 0.25	"	"	0.08 - 0.20
Zr: 0.05 - 0.25	"	"	0.12 - 0.18
Mn < 0.4	"	"	0.1 - 0.3
Zn < 0.3	"	"	< 0.1
Ni < 0.4	"	"	< 0.1

other elements < 0.10 each and 0.30 total, remainder aluminium.

The part is preferably solution heat treated, quenched and tempered to T6 or T7.

Description of the invention

The invention is based on the observation made by the inventors that if a small quantity of zirconium is added to a silicon alloy containing less than 1.5% of copper and less than 0.6% of magnesium, it is possible to obtain good mechanical strength and good creep resistance within the 250 - 300°C range of cast parts tempered to T6 or T7with no loss of ductility. This result is obtained without needing to use elements such as nickel or vanadium that cause problems in recycling. Furthermore, nickel has the disadvantage that it reduces the ductility of the part.

Like most alloys intended for the manufacture of engine cylinder heads, the alloy contains 5 to 11% of silicon and preferably 6.5 to 7.5%. Iron is kept below 0.6% and preferably below 0.3%, which means that primary or secondary alloys can be used, preferably primary alloys when a high elongation at failure is required.

Magnesium is a normal alloying element for alloys used in cylinder heads; if its content is equal to at least 0.15% and in combination with copper, it improves mechanical properties at 20 and 250°C. Beyond 0.6%, there is a risk of reducing the ductility at ambient temperature.

The addition of 0.3 to 1.5% and preferably 0.4 to 0.7% of copper can improve the mechanical strength without affecting the corrosion resistance. The inventors have also observed that within these limits, the ductility and strength of parts in the T6 or T7 temper when hot are not reduced. It also surprisingly transpired that the mechanical strength when hot and the creep resistance at 250°C are significantly improved if the contents of Cu and Mg in % increase jointly within the limits given above respecting the condition $0.3Cu + 0.18 < Mg < 0.6$.

At a content of more than 0.1%, manganese also has a positive effect on the mechanical strength at 250°C, but this effect reaches the maximum above a content of 0.4%. The titanium content is kept between 0.05 and 0.25%, which is fairly normal for this type of alloy. Titanium contributes to refining the primary grain during solidification, but in the case of alloys according to the invention, it works in liaison with zirconium and also contributes to the formation of very fine dispersoids (< 1 μm) of AlSiZrTi in the in-body part of the α-Al solid solution during the solution heat treatment of the cast part, these dispersoids being stable above 300°C, unlike the Al_2CuMg, AlCuMgSi, Mg_2Si and Al_2Cu phases that coalesce starting from 150°C.

These dispersoid phases do not cause embrittlement, unlike the large AlSiFe and AlSiMnFe iron phases (20 to 100 μm), and nickel phases that are formed during casting into interdendritic spaces.

Parts are made by normal casting processes, particularly chill casting by gravity and low pressure casting for cylinder heads, but also sand casting, squeeze casting (particularly in the case of insertion of composites) and lost foam casting.

Heat treatment comprises solution heat treatment typically for 3 to 10 h at a temperature of between 500 and 545°C, quenching preferably in cold water, waiting between quenching and annealing for 4 to 16 h and annealing from 4 to 10 h at a temperature between 150 and 240°C. The annealing temperature and

duration are adjusted so as to obtain either annealing to the peak mechanical strength (T6) or over-ageing (T7).

Parts according to the invention, and particularly cylinder heads and crankcases of automobile or aircraft engines, have a high mechanical strength, good ductility, and higher mechanical strength when hot and creep resistance than parts according to prior art.

Examples

Example 1

100 kg of an alloy A with the following composition (% by weight) was produced in the silicon carbide crucible in an electric furnace:

Si = 7.10 Fe = 0.15 Mg = 0.37 Ti = 0.14 Sr = 170 ppm

100 kg of alloy B with the same composition with an added 0.49% copper content

100 kg of alloy C with the same composition as B with an added 0.14% zirconium content.

These compositions were measured by spark emission spectrometry, except for Cu and Zr that were measured by induced plasma emission spectrometry.

Fifty AFNOR tensile chill test pieces were cast for each alloy. These test pieces were subjected to a heat treatment comprising solution heat treatment for 1 h at 540°C, preceded by a constant period of 4 h at 500°C for the copper alloys B and C to prevent burning, quenching in cold water, natural ageing at ambient temperature for 24 h and annealing for 5 h at 200°C.

Tensile test pieces and creep test pieces were machined from these test pieces so as to measure mechanical properties (ultimate strength R_m in MPa, yield stress $R_{p0.2}$ in MPa and elongation at failure A in %) at ambient temperature, at 250°C and at 300°C. The results are indicated in table 1:

Table 1

	R_m	$R_{p0.2}$	A	R_m	$R_{p0.2}$	A	R_m	$R_{p0.2}$	A
Temp.	Amb.	Amb.	Amb.	250°C	250°C	250°C	300°C	300°C	300°C
A	299	257	9.9	61	55	34.5	43	40	34.5
B	327	275	9.8	73	66	34.5	44	40	34.6
C	324	270	9.8	68	63	34.5	45	42	35.0

It is found that the addition of copper to alloy A improves the mechanical strength without modifying the elongation, both cold and hot, and that the addition of zirconium to B has almost no influence on the mechanical properties.

The next step was to measure the elongation (in %) after 100 h at 250°C and 300°C at different stresses (in MPa), on the creep test pieces for alloys B and C. Table 2 shows the result:

Table 2

Temperature (°C)	250	250	300
Stress (MPa)	45	40	22
A (%) alloy B	2.43	0.134	0.136
A (%) alloy C	0.609	0.079	0.084

It is found that for identical temperature and stress, alloy C with the added zirconium has a significantly better creep resistance, the deformation under constant load being reduced by 40 to 75% depending on the case.

Example 2

10 test pieces of each of the five alloys D to H were prepared under the same conditions as for alloy C, in example 1, varying the copper content and magnesium content within the preferred composition limits mentioned above. The compositions of the alloys are given in table 3:

Table 3

Alloy	Si	Cu	Mg	Zr	Ti
D	7.1	0.4	0.3	0.14	0.12
E	7.1	0.4	0.4	0.14	0.12
F	7.1	0.5	0.35	0.14	0.12
G	7.1	0.65	0.3	0.14	0.12
H	7.1	0.65	0.4	0.14	0.12

The mechanical properties at 20°C and 250°C were measured in the same manner. The results corresponding to the average of the values obtained on the test pieces of each alloy are given in table 4:

Table 4

Alloy	R_m(MPa)	$R_{0.2}$(MPa)	A (%)	R_m(MPa)	$R_{0.2}$(MPa)	A (%)
	20°C	20°C	20°C	250°C	250°C	250°C
D	301	250	8.9	69	60	44.5
E	325	282	7.6	77	66	36.3
F	320	271	8.7	74	63	41.5
G	315	259	9.1	71	60	45.2
H	339	291	8.7	81	69	39.6

Within the tested composition limits, it is found that the ultimate strength and the yield stress increase as the Cu and Mg contents increase, but that elongation is not very much affected. At 250°C, the increase in the Mg content from 0.3 to 0.4% has a very good effect on the ultimate strength and the yield stress, particularly for the alloy with the highest copper content (H).

Furthermore, for an equal copper content, the increase of the magnesium content from 0.3 to 0.4% improves the creep resistance at 250°C, as can be seen

from the results of the creep tests at a stress of 40 MPa after 100, 200 and 300 h for alloys G and H, as indicated in table 5:

Table 5

Duration	100h	200h	300h
$\dot{\varepsilon}$ (%) G	0.098	0.48	1.20
ε (%) H	0.078	0.18	0.31

Example 3

Test pieces of 6 alloys I to N with the compositions indicated in table 6 were prepared in the same way as for alloy C in example 1:

Table 6

Alloy	Si	Cu	Mg	Mn	Zr	Ti
I	7	0.5	0.3	-	0.14	0.12
J	7	0.5	0.3	0.15	0.14	0.12
K	7	1	0.3	-	0.14	0.12
L	7	1	0.3	0.15	0.14	0.12
M	7	1	0.3	0.25	0.14	0.12
N	7	1	0.5	0.25	0.14	0.12

Mechanical properties were measured at 250°C and table 7 shows the results:

Table 7

Alloy	R_m (MPa)	$R_{0.2}$ (MPa)	A (%)
I	73	62	45
J	76	65	37
K	70	59	46
L	77	62	47
M	77	62	46
N	90	75	33

It can be found that the addition of 0.1 to 0.3% of manganese increases the mechanical strength at 250°C by at least 5%. However, there is no increase between 0.15 and 0.25%. Finally, for an alloy N with high copper content, the increase in the magnesium content from 0.3 to 0.5% gives a spectacular and unexplained increase in the mechanical strength when hot.